

# Status of the NOvA Experiment

**Denis Perevalov, Fermi National Accelerator Laboratory**

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# Overview

- Neutrino Oscillations Overview
- Latest  $\theta_{13}$  Measurements
- NOvA Experiment Introduction
- Current Status
- Summary



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# Neutrinos Have Mass!

$$(\nu_e, \nu_\mu, \nu_\tau)^T = U (\nu_1, \nu_2, \nu_3)^T \quad U = \text{matrix PMNS}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 angles, 1 complex phase

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \frac{\Delta m_{ij}^2 L}{4E} \mp 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \frac{\Delta m_{ij}^2 L}{2E}$$

$$\Delta m_{ij}^2 = m_j^2 - m_i^2 \quad \underline{\text{2 mass differences}}$$



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# PMNS Mixing Matrix

$$\begin{array}{c}
 \text{atmospheric } \nu \\
 \left( \begin{array}{ccc} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{array} \right)
 \end{array}
 \begin{array}{c}
 \text{leptonic CP phase } \delta \\
 \left( \begin{array}{ccc} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{array} \right)
 \end{array}
 \begin{array}{c}
 \text{solar } \nu \\
 \left( \begin{array}{ccc} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{array} \right)
 \end{array}$$

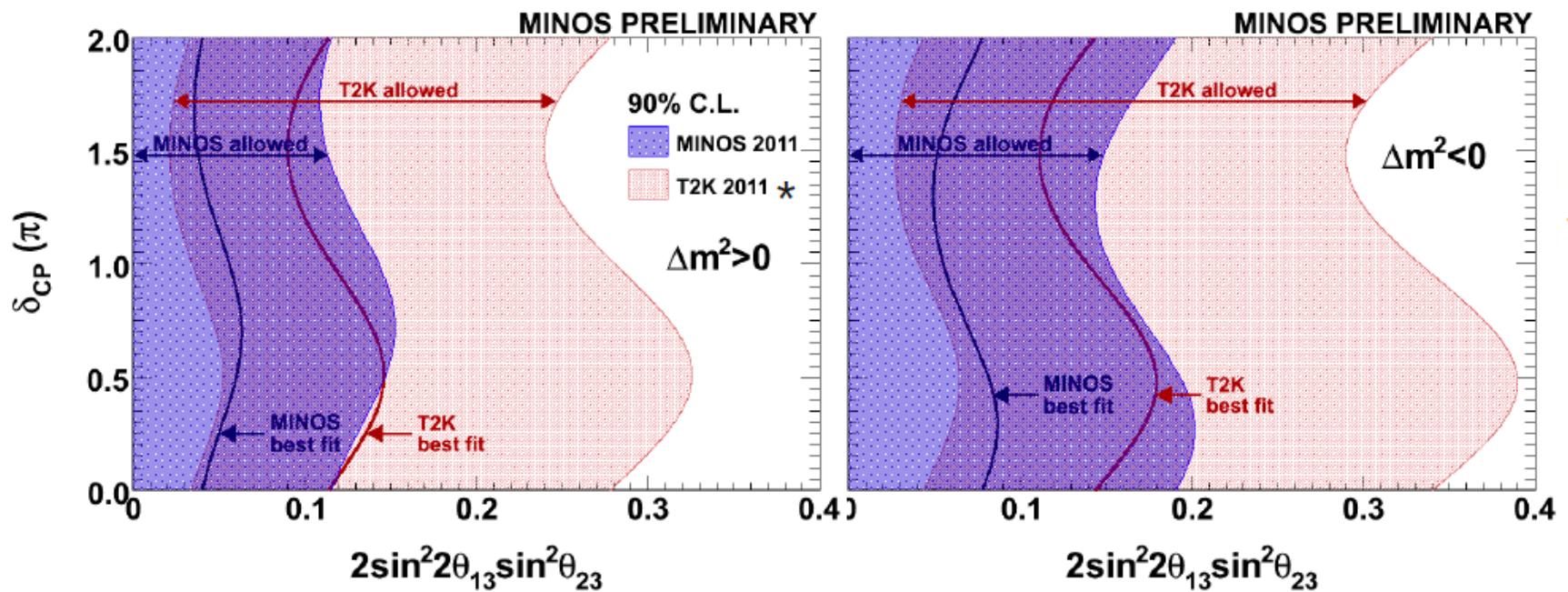
## Global Fit

parameter	best fit $\pm 1\sigma$	$2\sigma$	$3\sigma$	
$\Delta m_{21}^2 [10^{-5}\text{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19	Kamland
$\Delta m_{31}^2 [10^{-3}\text{eV}^2]$	$2.45 \pm 0.09$ $-(2.34^{+0.10}_{-0.09})$	2.28 – 2.64 $-(2.17 - 2.54)$	2.18 – 2.73 $-(2.08 - 2.64)$	MINOS
$\sin^2 \theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36	SNO
$\sin^2 \theta_{23}$	$0.51 \pm 0.06$ $0.52 \pm 0.06$	0.41–0.61 0.42–0.61	0.39–0.64	Super-Kamiokande
$\sin^2 \theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	$\leq 0.027$ $\leq 0.031$	$\leq 0.035$ $\leq 0.039$	Chooz



# Latest $\theta_{13}$ Results

## T2K and MINOS comparison



\* arXiv:1106.2822

*arXiv:1108.0015 (MINOS)  
PRL 107, 041801 (T2K)*



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# Tevatron at Fermilab



# The NOvA Experiment

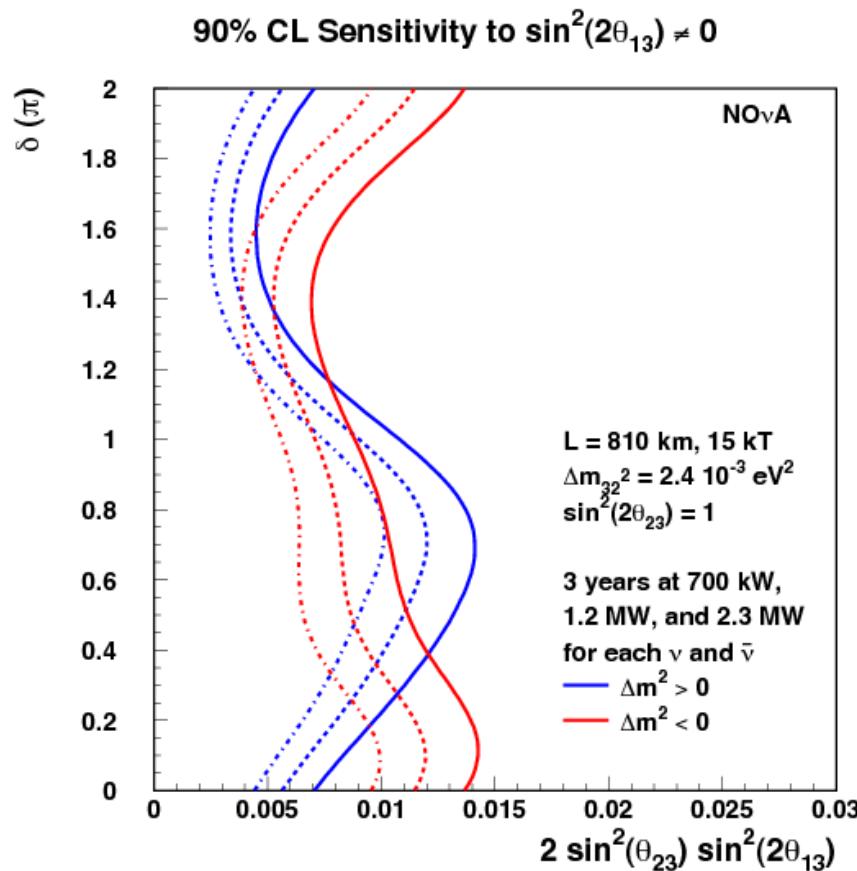
- Long baseline neutrino oscillation experiment:
  - Near and far detector pair.
  - 14.5 mr off-axis in order to have a narrow neutrino flux with energy peak is at 2GeV
  - 810 km baseline from Fermilab to Ash River, Minnesota
- Goals:
  - **Search for  $\nu_\mu \rightarrow \nu_e$  transitions in order to measure/limit  $\theta_{13}$**
  - precision measurements of  $|\Delta m^2|$ ,  $\theta_{23}$
  - determine mass hierarchy
  - constrain CP violating phase



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# $\theta_{13}$ Sensitivity



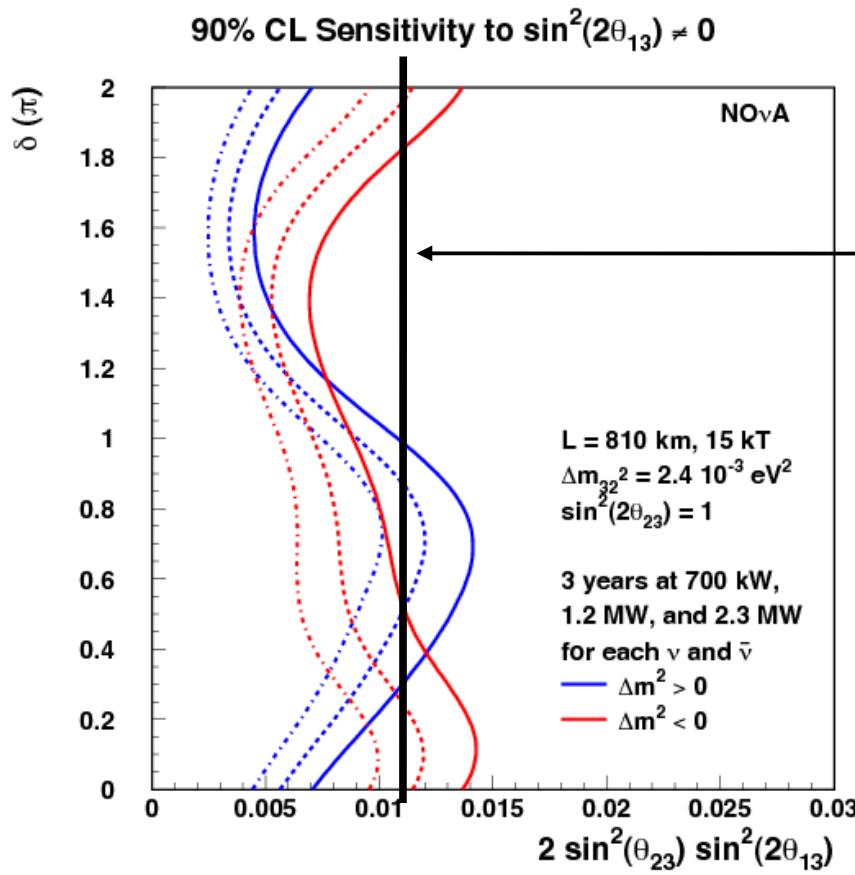
- NOvA is sensitive to electron neutrino appearance down by an order of magnitude at 90% CL.
- Sensitivity to  $\sin^2(2\theta_{13})$  after 3 years each of running  $\nu$  and  $\bar{\nu}$  beams
- $18 \times 10^{20}$  POT in each neutrino and antineutrino mode



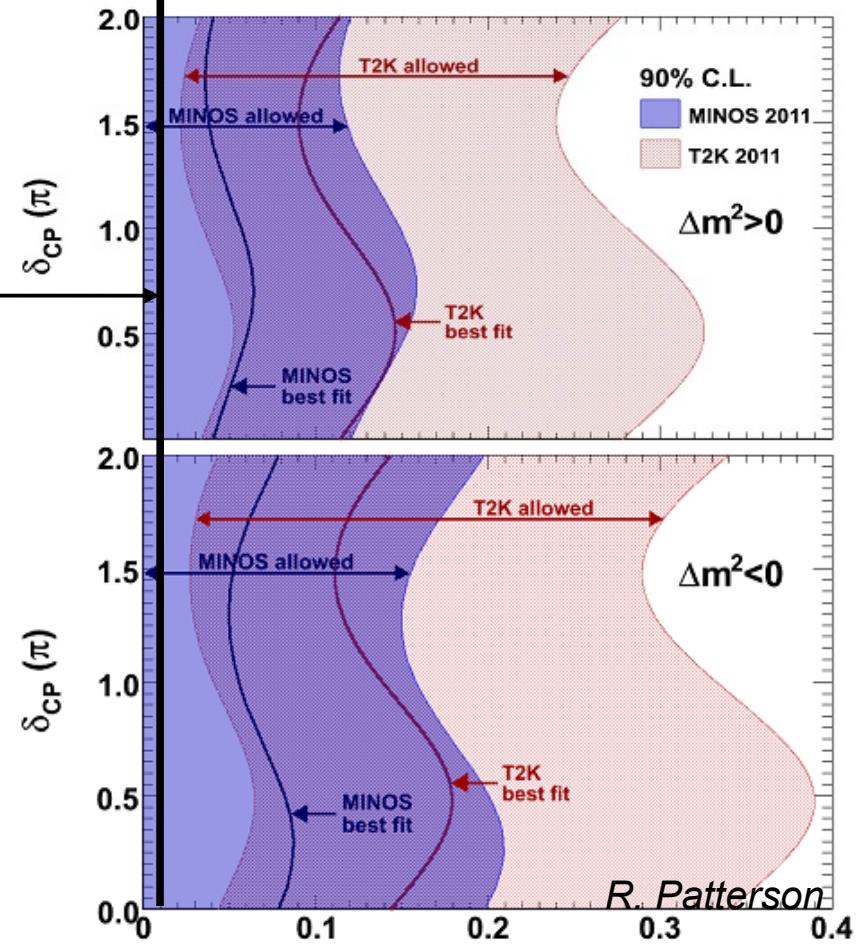
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# $\theta_{13}$ Sensitivity



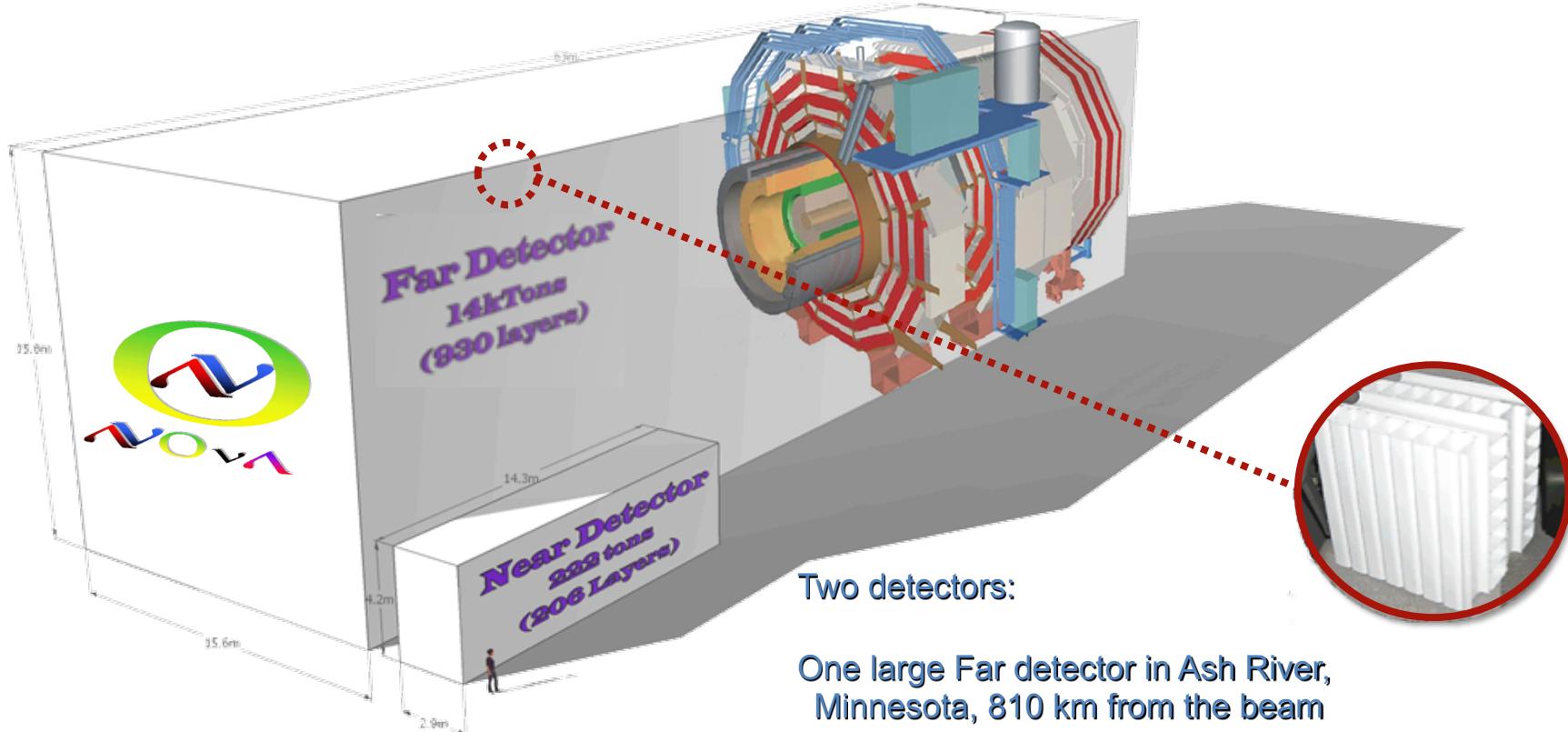
Overlay of MINOS and T2K allowed regions



arXiv:1108.0015 (MINOS)  $2\sin^2 2\theta_{13} \sin^2 \theta_{23}$   
PRL 107, 041801 (T2K)



# NOvA Detectors



Two detectors:

One large Far detector in Ash River, Minnesota, 810 km from the beam target. 14 kTons, 357,120 channels.

One small 222 tons detector at Fermilab site about 1 km from the beam target.

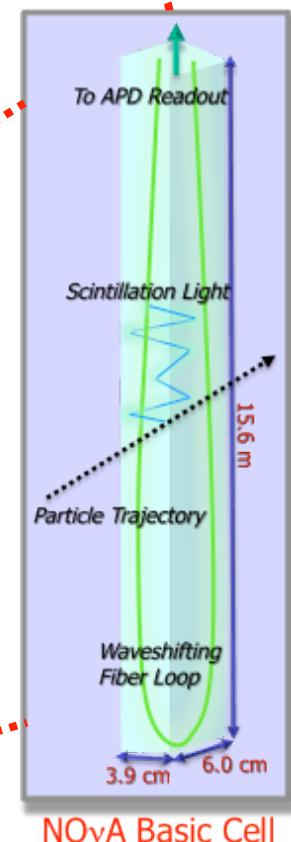
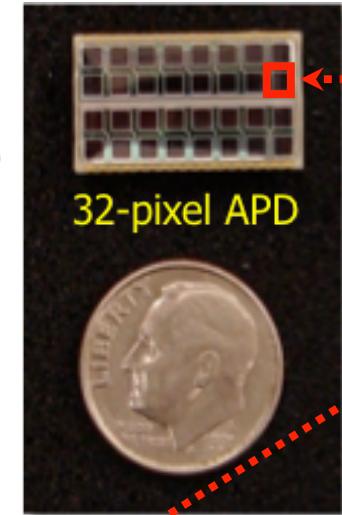
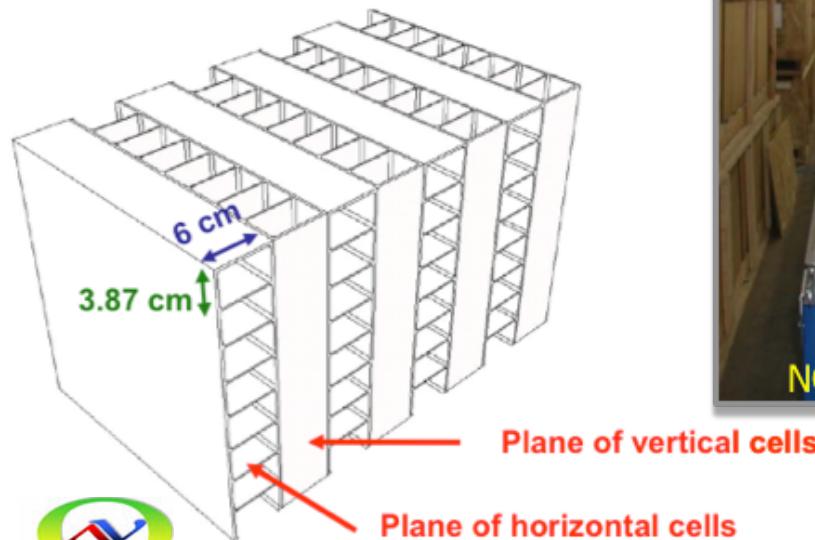
Alternating X and Y planes

Filled with liquid scintillator



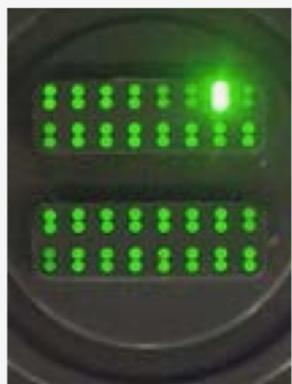
# Detector Technology

- Detectors composed of highly reflective PVC extrusions (15% TiO<sub>2</sub>)
- - 24 extrusions/plane in Far detector (384 cells/plane)  
- 357,120 cells in Far Detector
- Extrusions filled with liquid scintillator (mineral oil + 5% pseudocumene)
- Each cell read out by a wavelength-shifting fiber into one pixel of a 32-pixel avalanche photodiode (APD), 30 p.e. from far-end of cell into APD

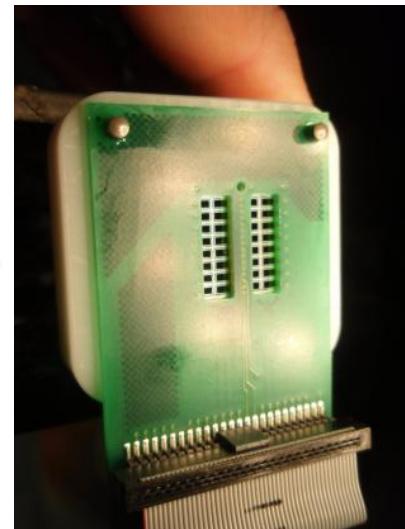


## Electronics

End of Fibers



Avalanche photo-diode (APD)



Front-end-board (FEB)



The photon signal from fibers is read by an Avalanche Photo-Diode (APD), where it is amplified.

The APD output is then digitized by the Front-End-Board (FEB)

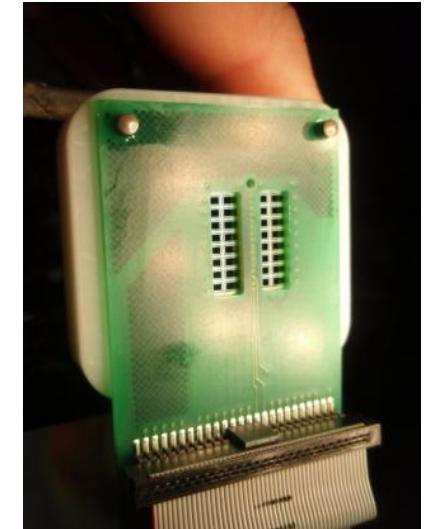


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## Avalanche photo-diode (APD)

- Made by Hamamatsu
- Relatively cheap (~ \$400 a piece)
- Array of 32 pixels
- 85% QE for 520 – 550 nm light.
- Gain of 100 @ 375 volts.
- Actively cooled to -15 C.
- Requires 20 pe signal from MIP at far end of cell with 10-15 pe threshold.
- About 12,000 APDs on FEBs at the Far detector (496 in Near Detector)

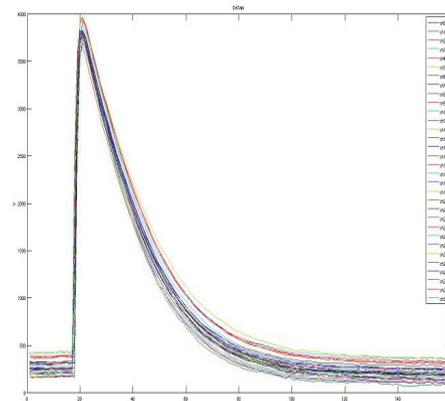


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## Front-end-board (FEB)

- Low noise ASIC amplifier is developed to maximize the sensitivity to small signals from the fiber.
- Analog-to-Digital converter samples each pixel with a frequency of 2 MHz (8 MHz at the Near Detector)
- Field Programmable Gate Array preselects “hits” if the ADC value change passes a threshold and sends the readout information to DCM.



- Thermo Electric Cooler Controller constantly gets current temperature on the APD surface and controls the amount of drive current to supply for a Thermo Electric Cooler installed on the APD module.

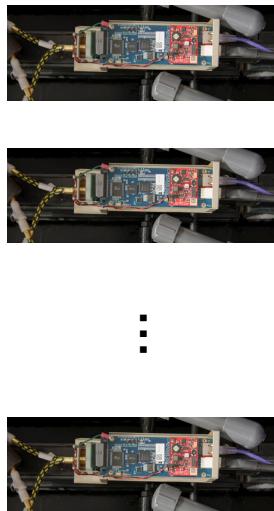


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## Data Acquisition System

64 FEBs



Data Concentrator Module (DCM)



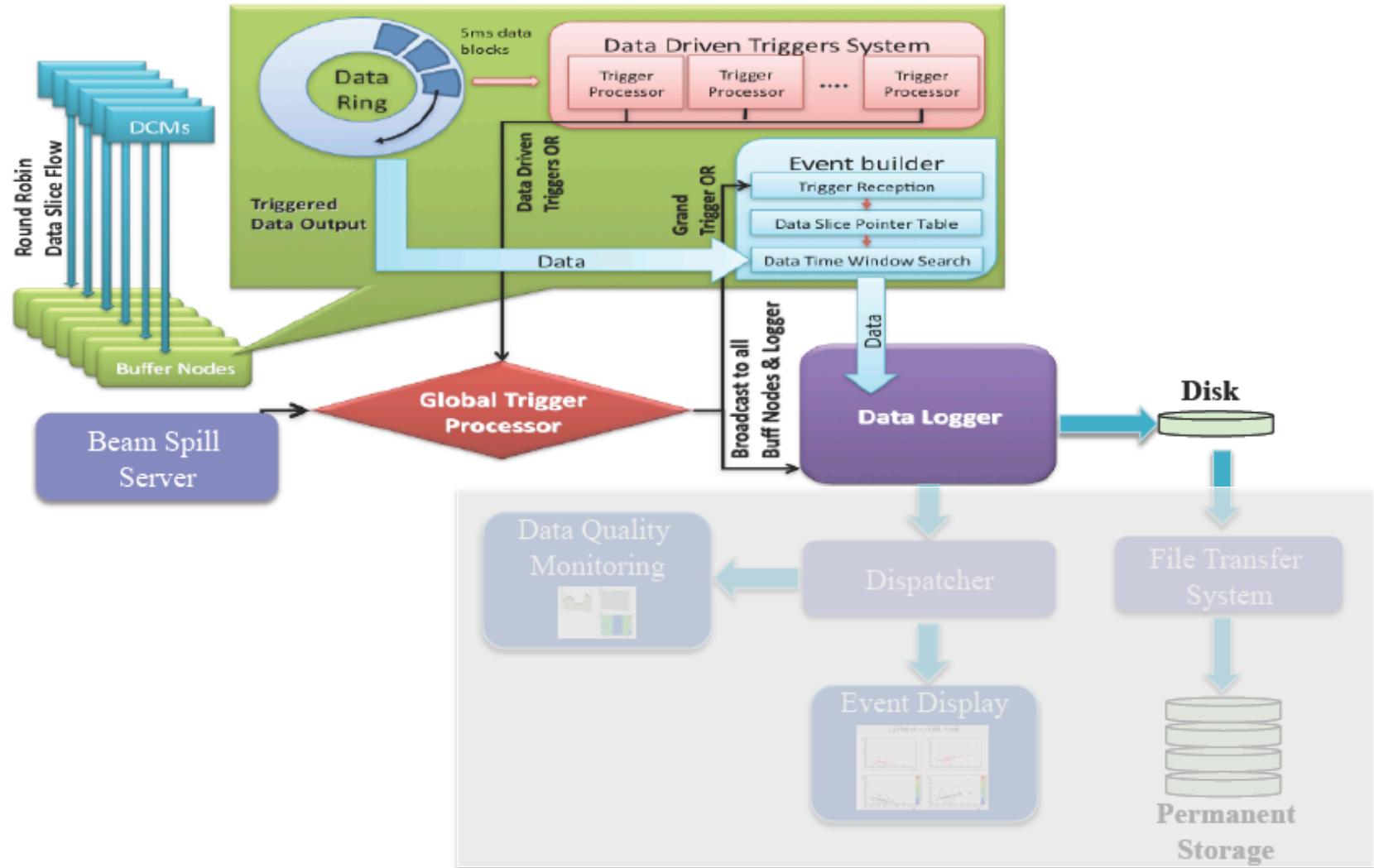
- 64 FEBs provide input to the Data Concentrator Module (DCM)
- DCM packetize the data and sends it through the Gigabit Ethernet to Buffer Nodes
- No data loss at this stage of the data transmission



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# Data Acquisition System



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## Status and Timeline

### NuMI Beam:

Upgrade from 320 kW to 700 kW

In order to achieve this...

Accelerator shutdown: March 2012

### Far Detector:

Construction starting January 2012

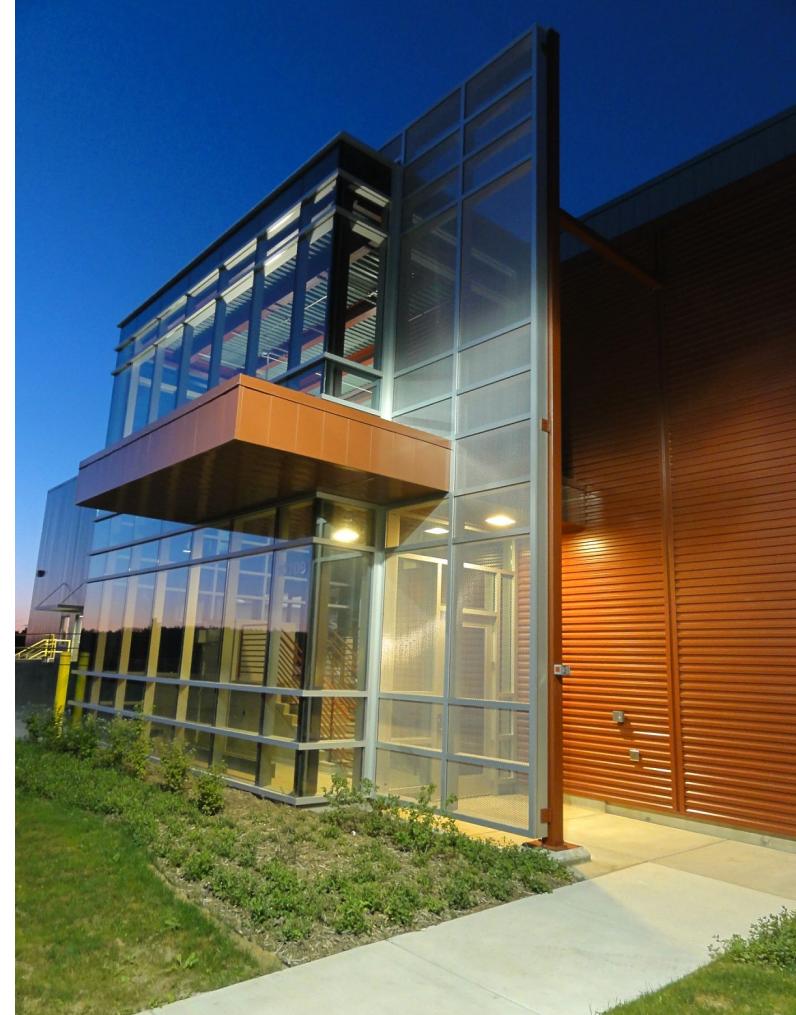
- 50% completion by end of shutdown
- Complete by early 2014

### Near Detector:

- Cavern excavation during shutdown

### Prototype Near Detector on Surface (NDOS):

- Running since October 2010...



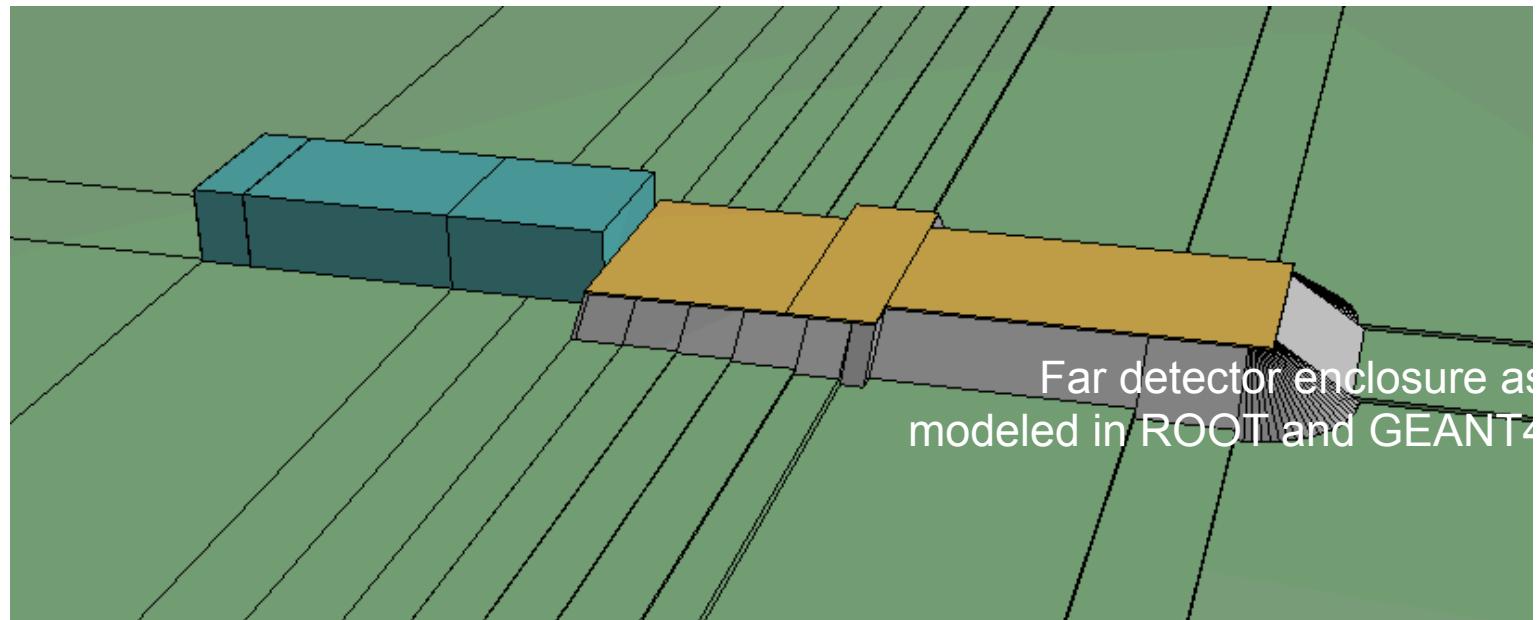
Far Detector entrance



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## Far Detector (detector simulation)



*Experiment progress:*  
**Far detector laboratory complete**

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- After many years of looking at this. We can now look at this...

## Far Detector (from helicopter)



*June 4, 2011*

*Experiment progress:*  
**Far detector laboratory complete**

- Beneficial occupancy of Ash River laboratory on April 13, 2011

## Far Detector (detector hall)



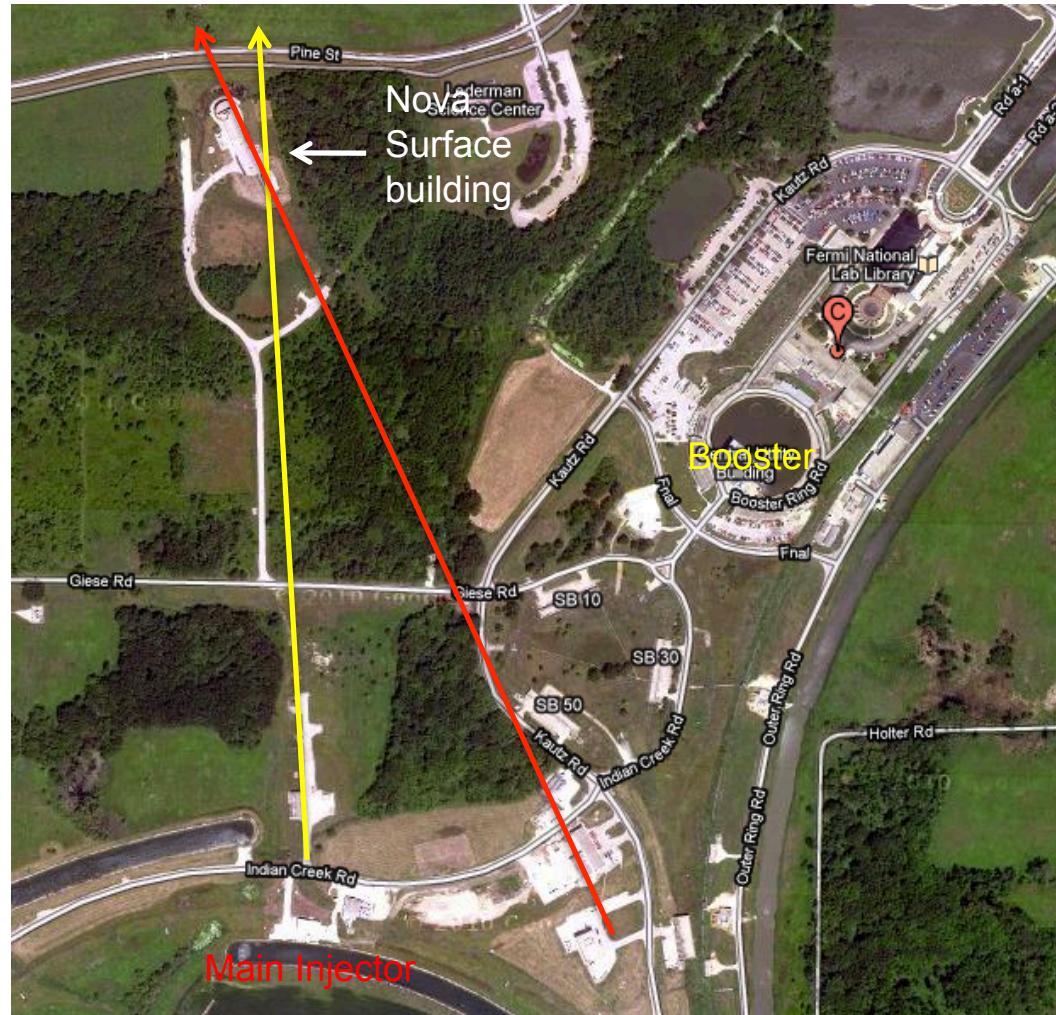
*Experiment progress:*  
**Far detector laboratory complete**

- Inside the detector enclosure looking south

## Prototype Near Detector on Surface (NDOS)



- Located in two neutrino beams providing an early look at data and a chance to tune up DAQ, calibration, reconstruction, and analysis prior to first data from Ash River
- NDOS is located directly above the NuMI neutrino beam line and is oriented parallel to the NuMI beamline. It sees neutrinos at an off-axis angle of 110 mrad.
- NDOS is located ~on the Booster Neutrino Beam (BNB) line about 650m downstream.

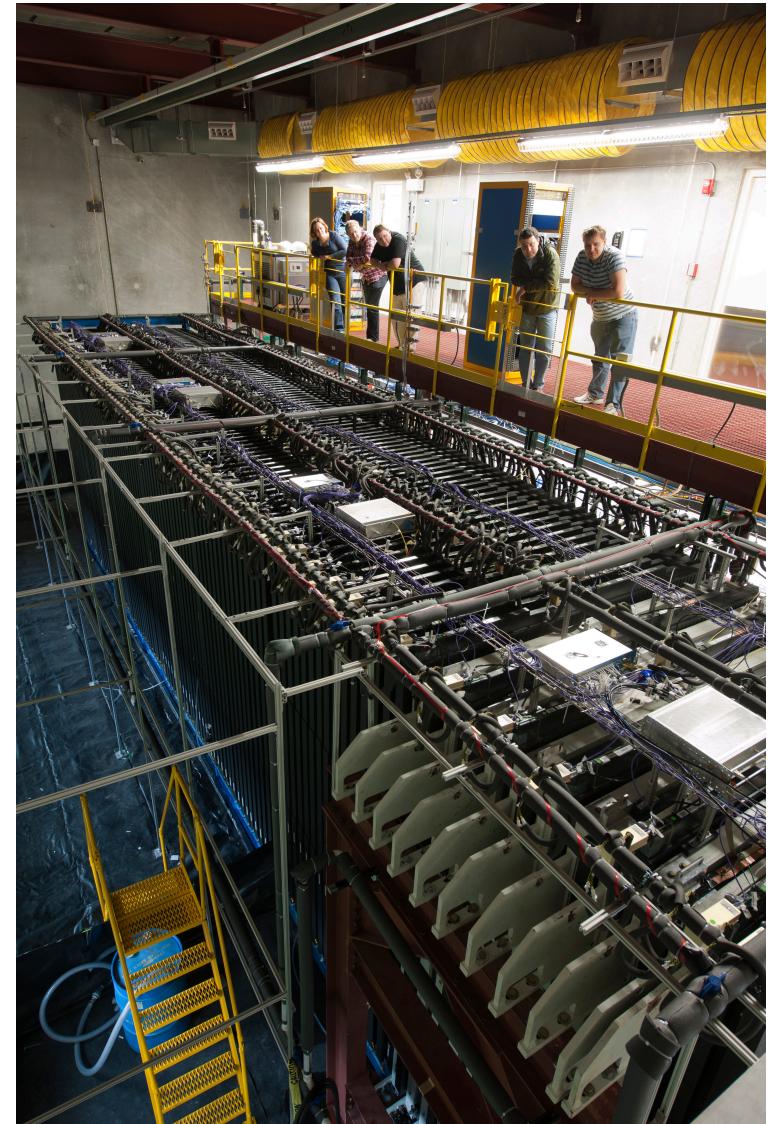


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# Prototype Near Detector on Surface (NDOS)

- Very similar design and scale to the actual NOvA Near Detector
- Installed and collecting data
- Run Goals:
  - **Testing**
    - Test detector design and installation procedures
    - Exercise calibration scheme
    - Benchmark MC
    - Demonstrate electron neutrino selection, background suppression
    - Verify cosmic background suppression
  - **Physics**
    - Study nuclear hadronization models
    - Quasi-elastic cross section at 2 GeV
    - Constrain neutrino flux
    - Booster short-baseline oscillations



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# Prototype Near Detector on Surface (NDOS)

## Lessons Learned...

- **22% manifolds developed cracks.**
  - Redesign of manifolds
  - Splints to fix NDOS
  - Changes to pressure testing
- **50% APDs were lost due to a bad installation or sealing issues and a subsequent cooling.**
  - APD assembly in a clean room
  - Strict installation procedures
  - Redesign of the APD module
  - APD and FEB surface coding
  - APD module sealing test
- **Electronics noise induced by a thermo electric cooler controller**
  - Redesign of the TECC board
  - Using ferrite beads

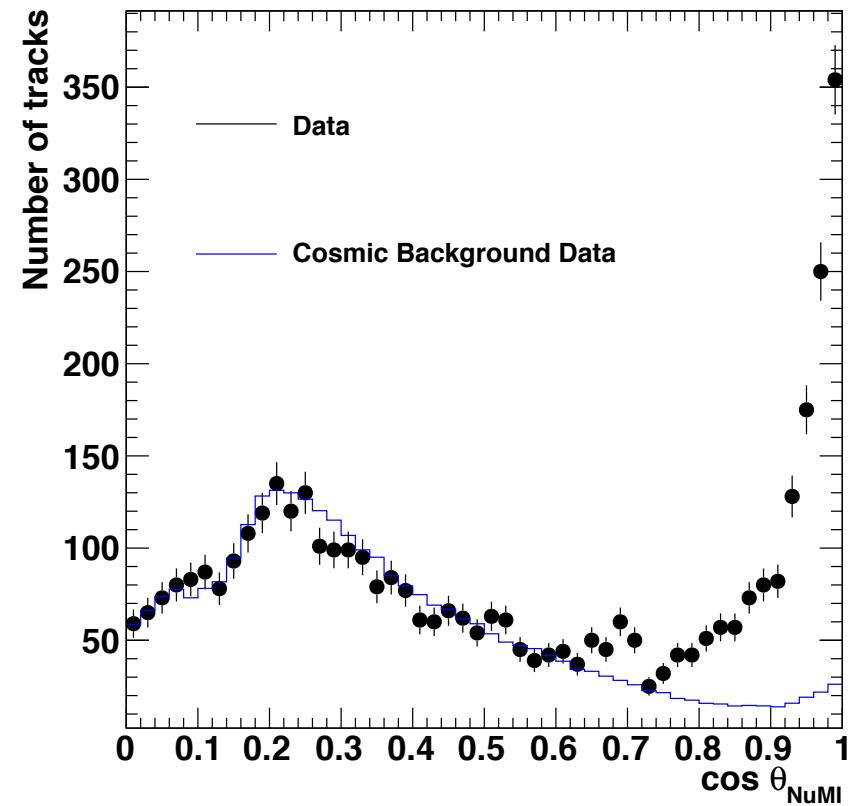
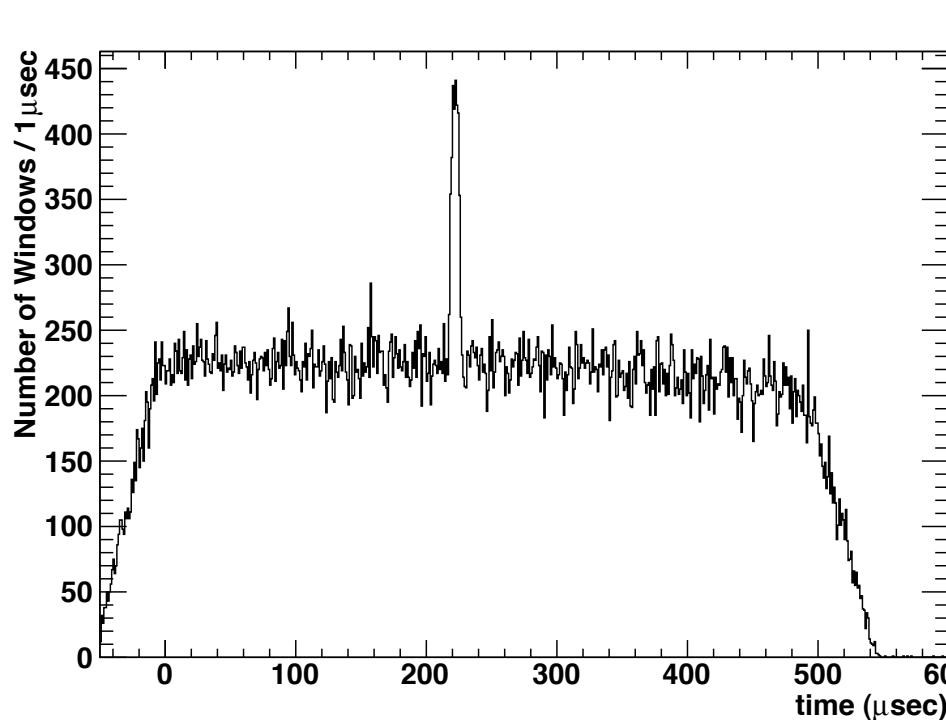


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# Prototype Near Detector on Surface (NDOS)

## NuMI Neutrinos



We do observe the neutrinos from the NuMI beamline

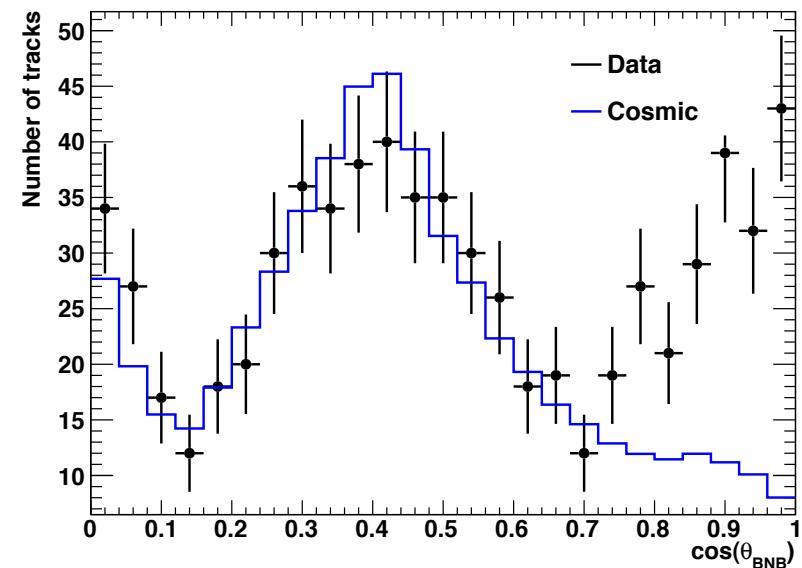
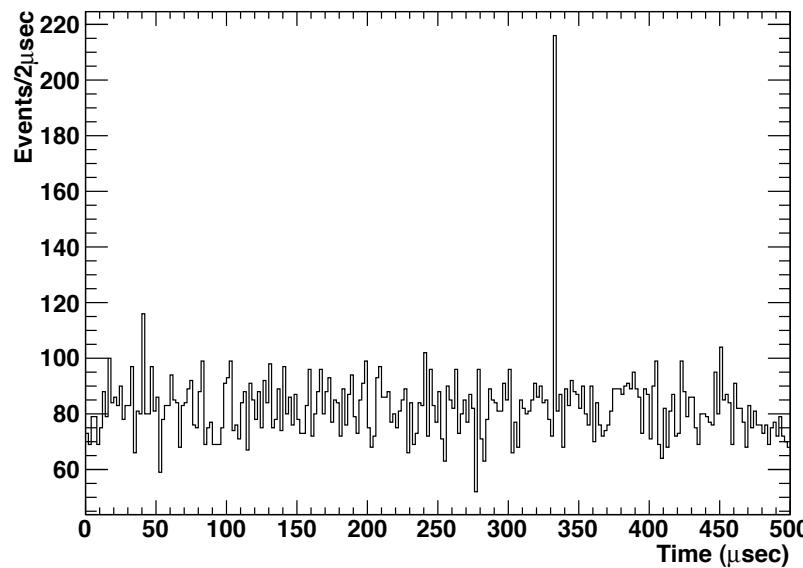


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# Prototype Near Detector on Surface (NDOS)

## Booster Neutrinos



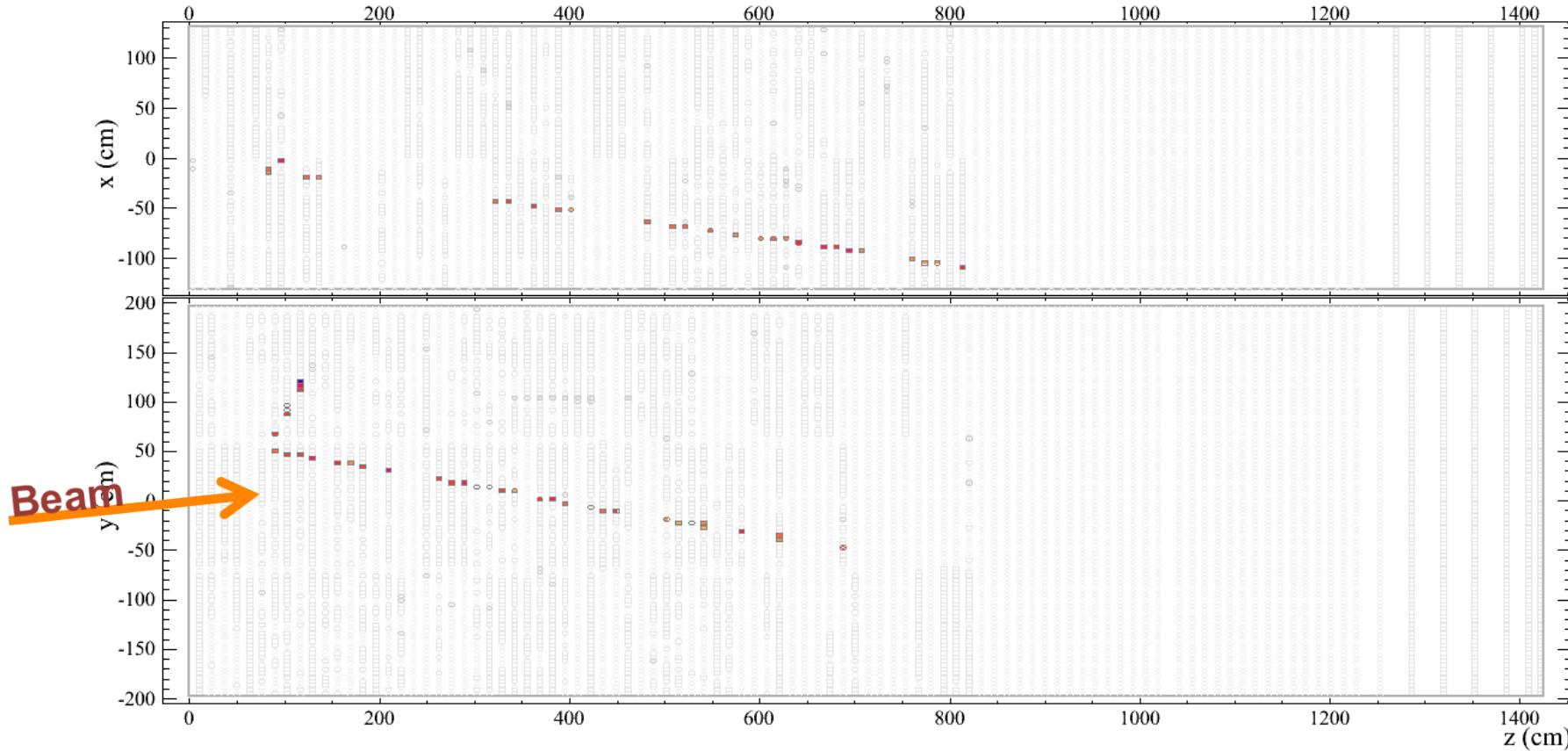
We do observe the neutrinos from the Booster beamline



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# NDOS Neutrino candidates

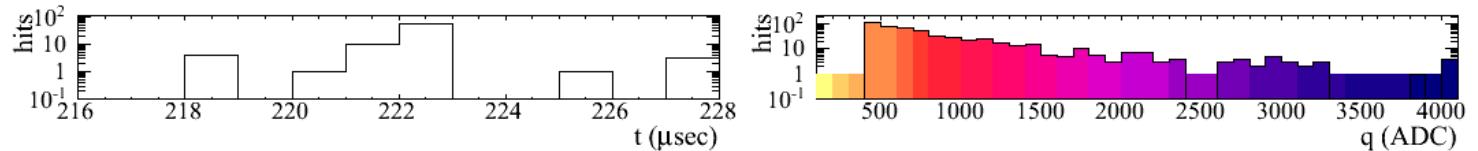


**NOvA - FNAL E929**

Run: 10893/8

Event: 314724

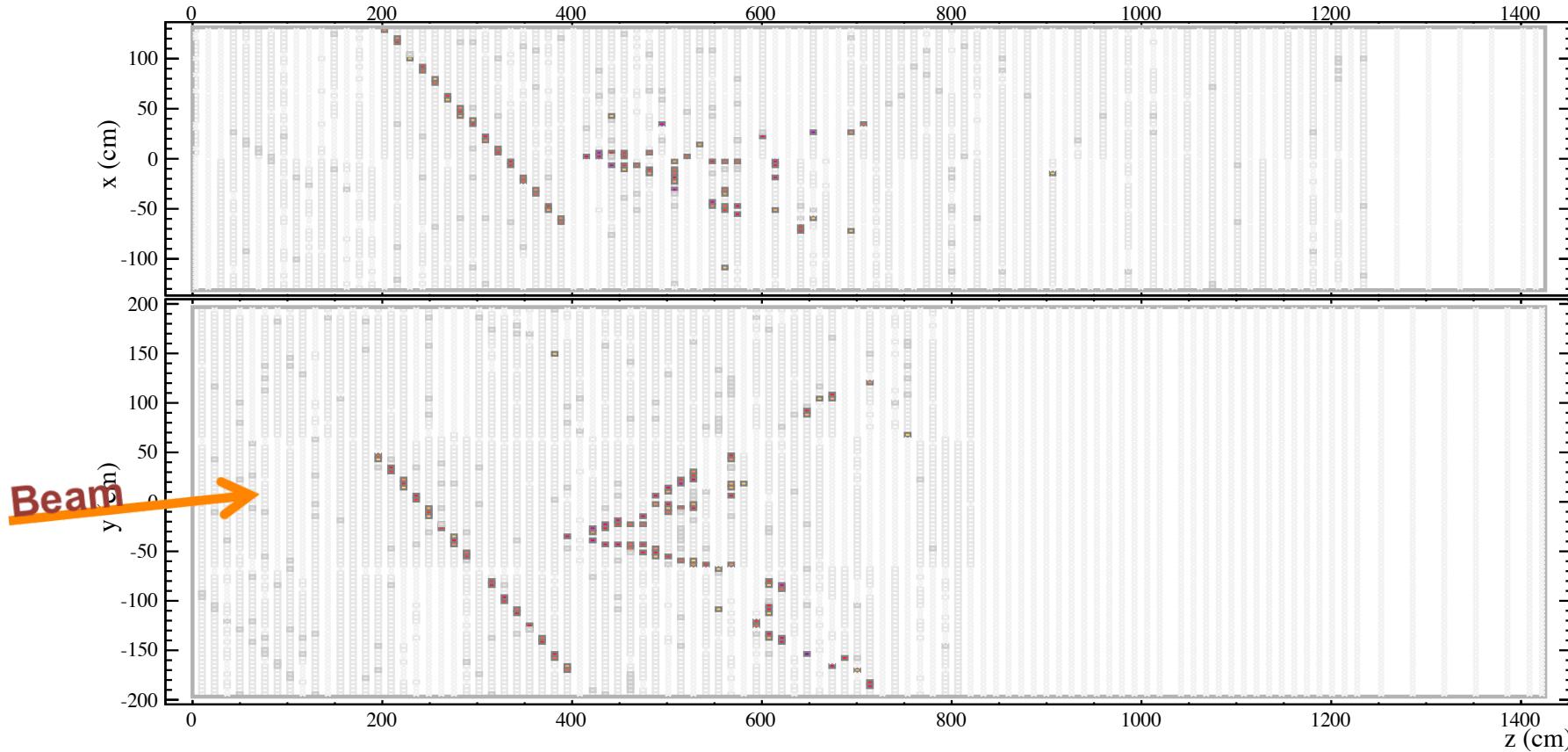
UTC Tue Dec 21, 2010  
11:48:18.997623872



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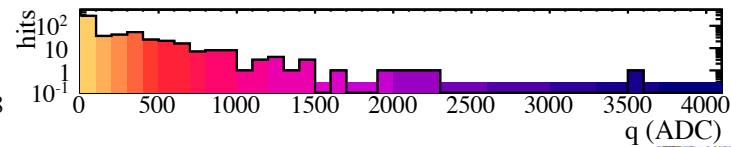


# NDOS Neutrino candidates



**NOvA - FNAL E929**

Run: 11956/6  
 Event: 273516  
 UTC Mon Apr 11, 2011  
 00:35:22.853571392

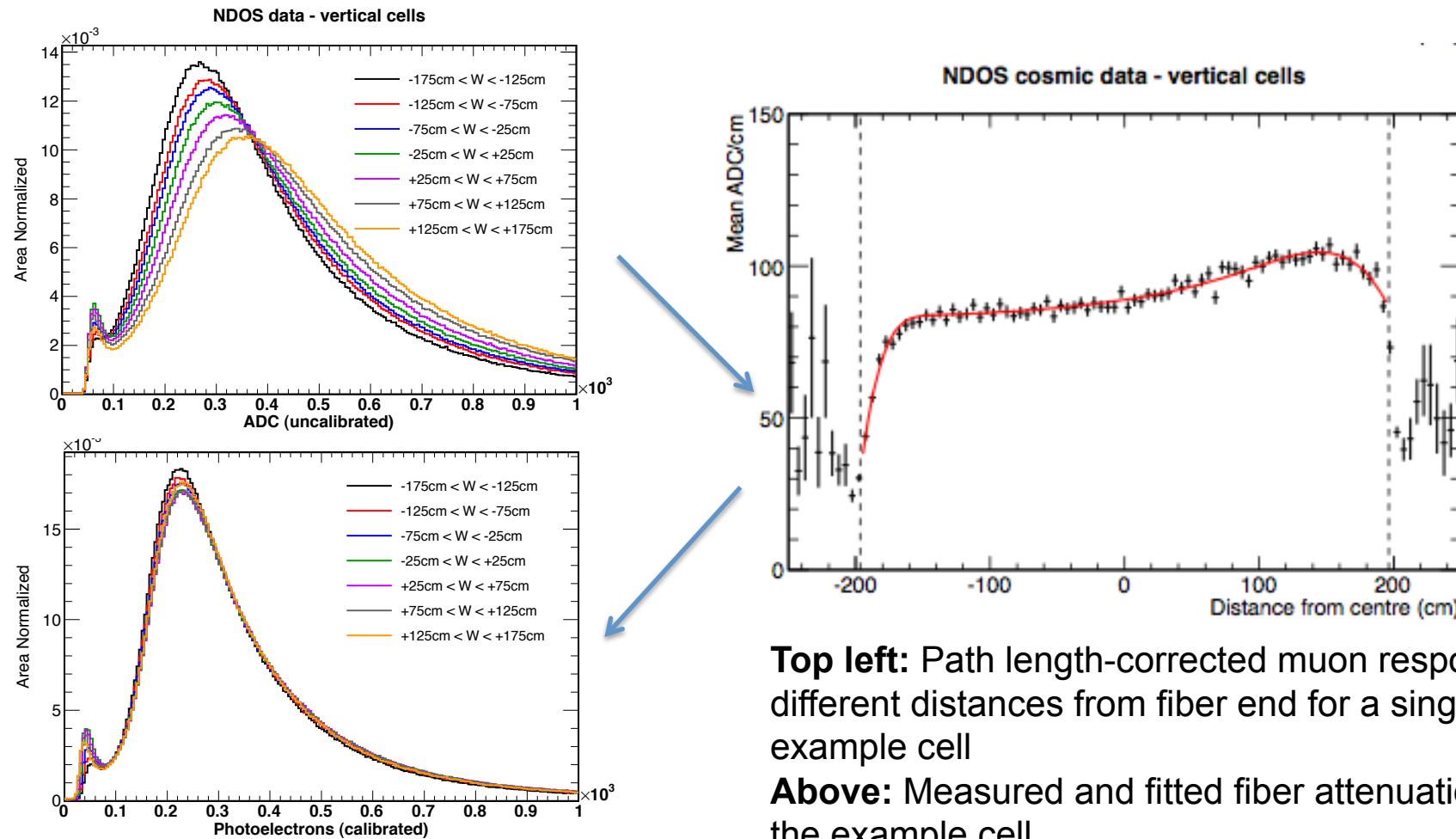


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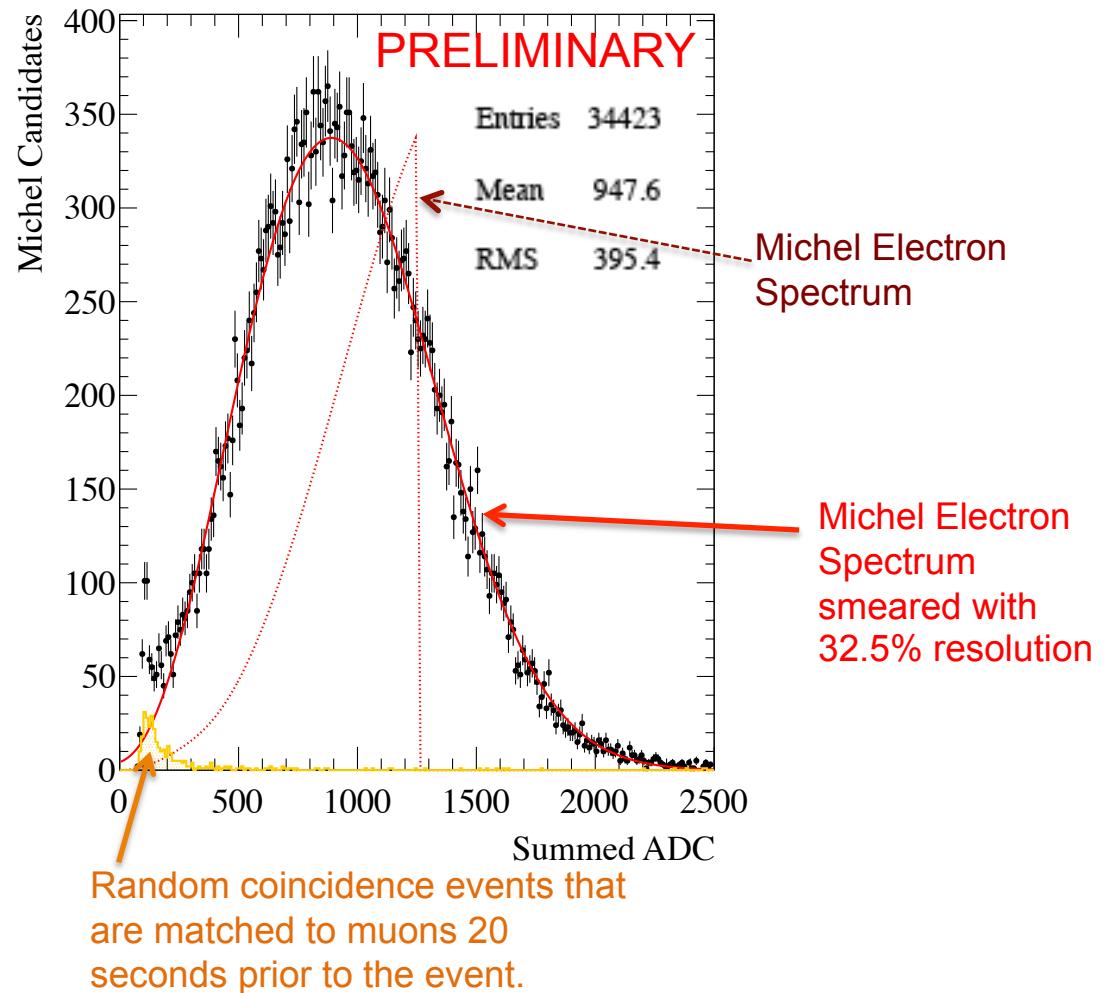
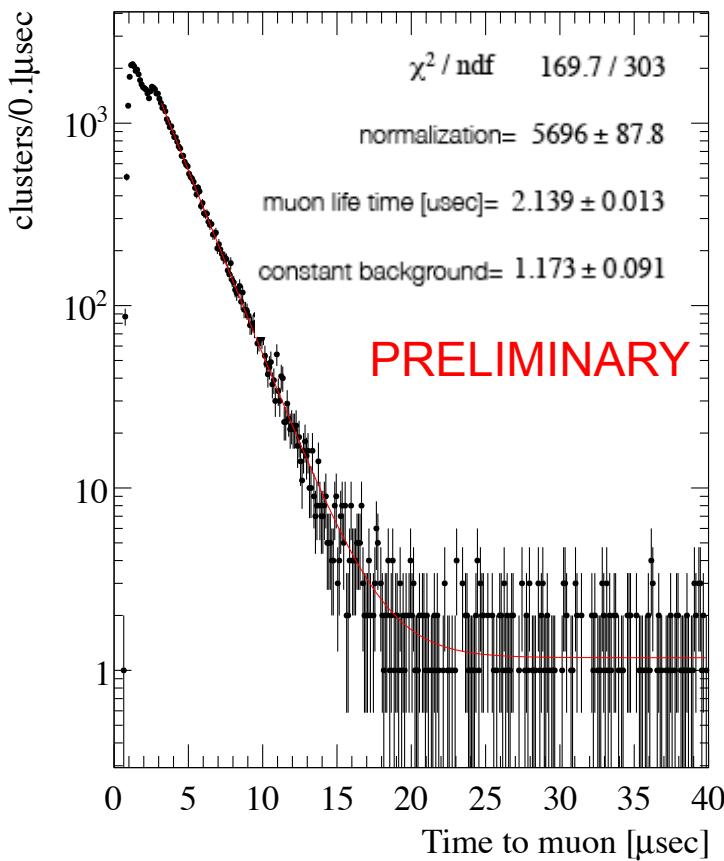
# Calibration

## Attenuation



# Calibration

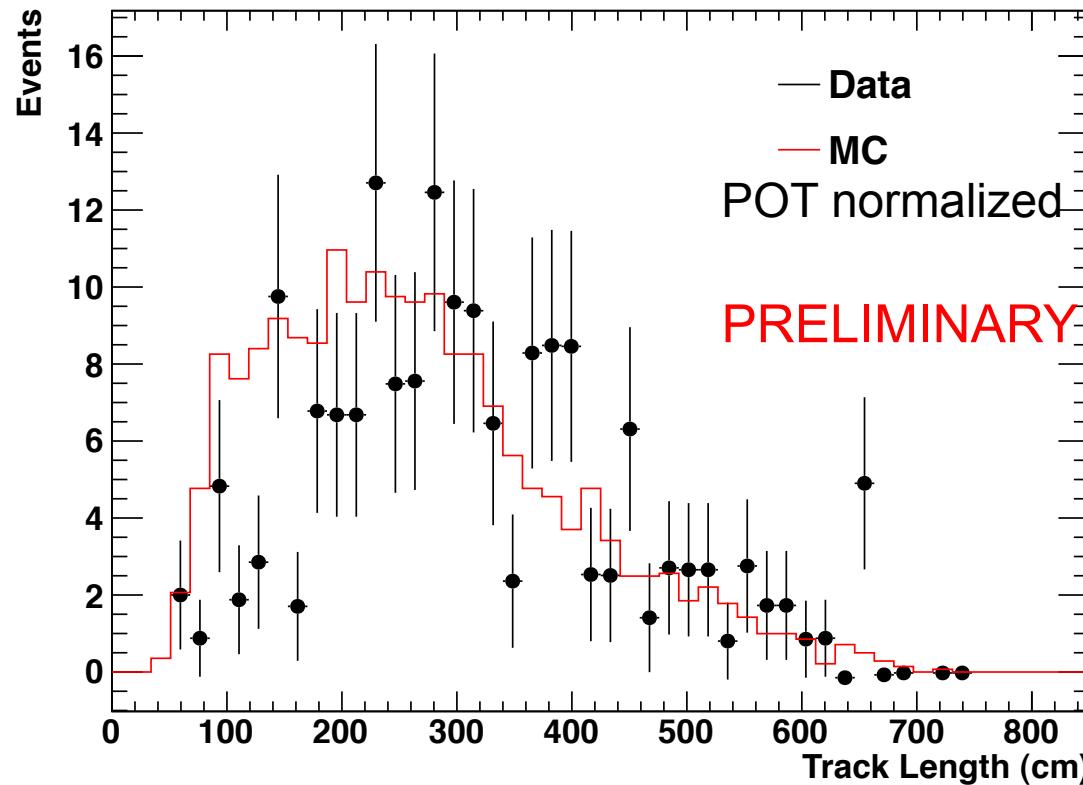
## Michel Electron Energy Spectrum



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## Event Rate



- Early look at contained events indicates NuMI MC event rate agrees with data



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# Conclusions

- NOvA has become the leading experiment at Fermilab
- Recent results from T2K are very encouraging for the NOvA program.
- NOvA NDOS is taking data now and has provided critical feedback to all aspects of the experiment.
- Far Detector construction is fast approaching so please ...  
*Stay Tuned!*

140 Collaborators in 26 Institutions from 4 Countries



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# BACKUP



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# Importance of $\theta_{13}$

- Fundamental physics parameter
- In PMNS matrix,  $\theta_{13}$  is tied to the Dirac CP-violating phase  $\delta$ . If  $\theta_{13}=0$ , then there is no way to determine CP violation in the lepton sector using neutrino oscillations.
- CP-violating phase  $\delta$  is crucial for CP violation measurements in leptonic sector.
- If  $\delta$  is large enough, one can determine the mass hierarchy using neutrino oscillation measurements.



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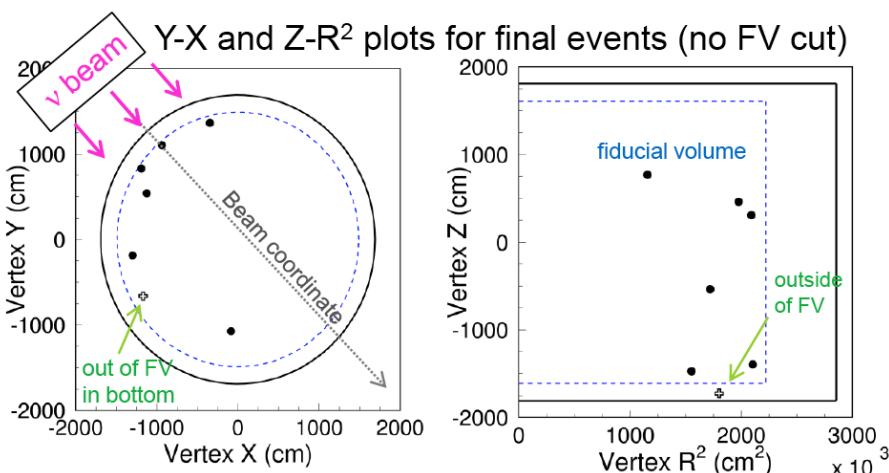


# Latest $\theta_{13}$ Results

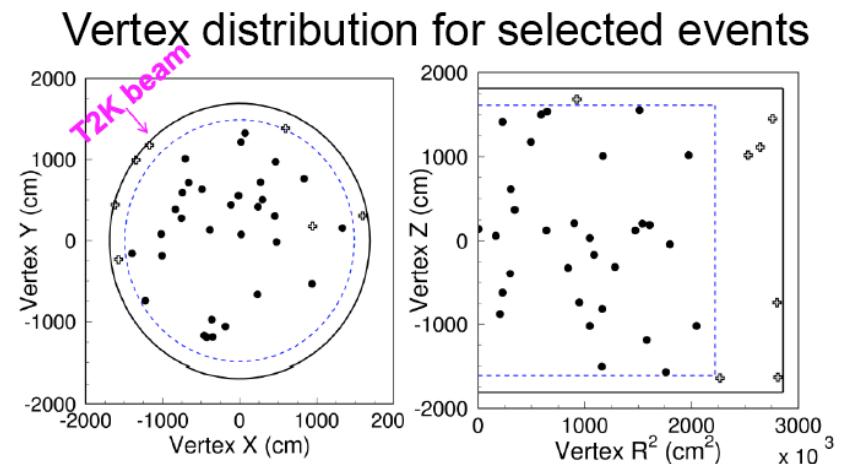
## T2K

The T2K result is remarkable, but there are questions...

$\nu_e$  candidates



$\nu_\mu$  candidates



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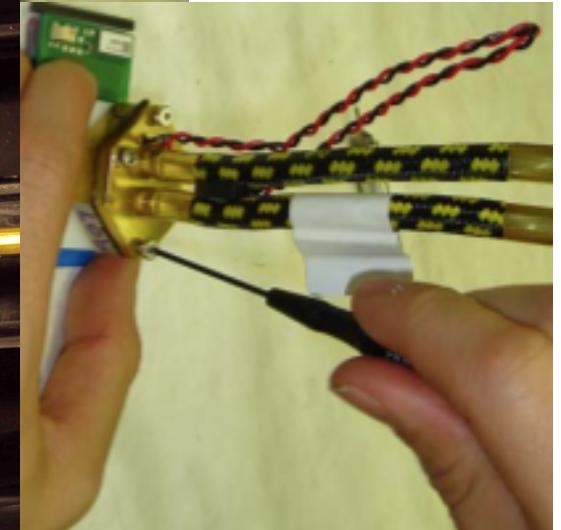
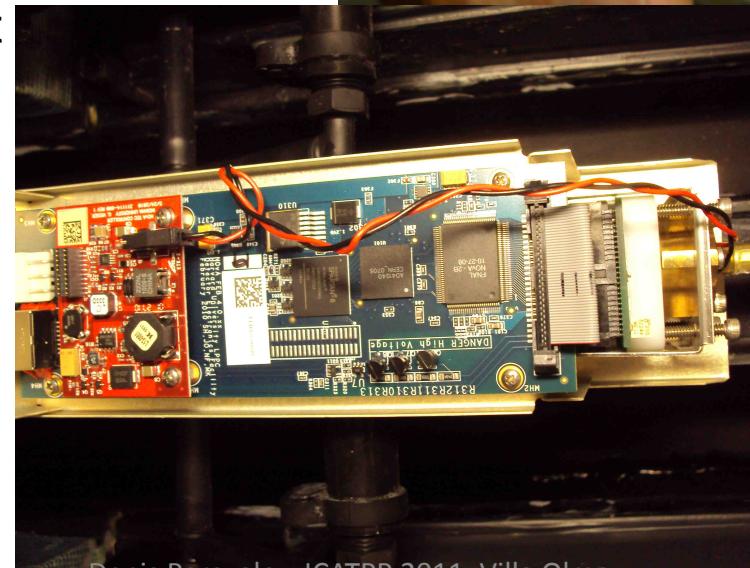
# APD Cooling

APDs are going to be cooled by thermoelectric coolers (TEC) to **-15°C**.

Thermistor reads a temperature of the APD and sends it to the FEB.

FEB has a TEC Controller board that regulates the current supplied to the TEC.

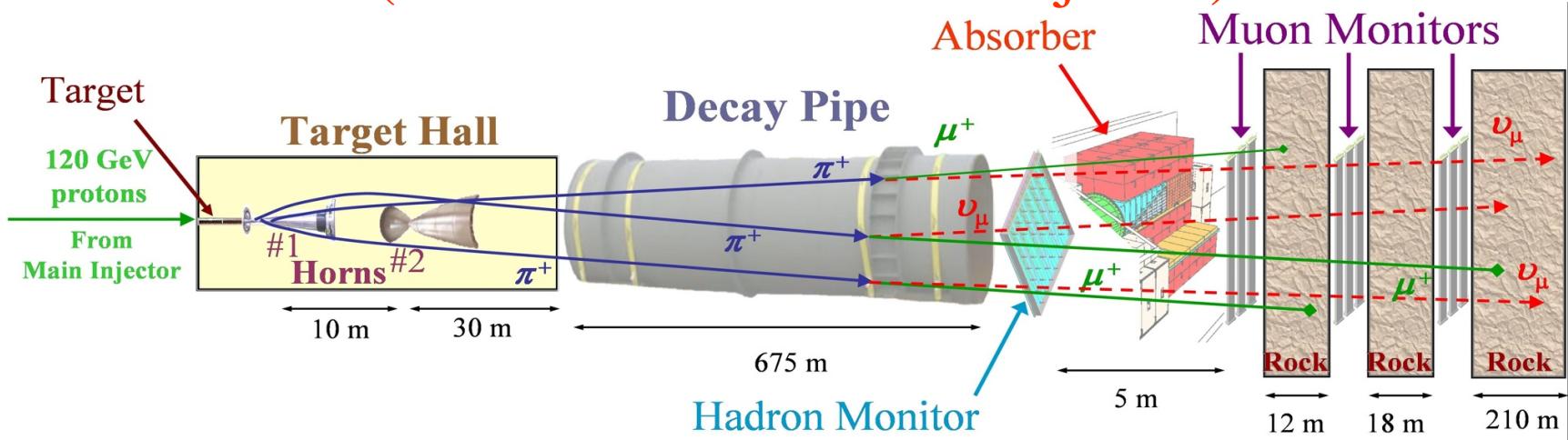
The heat generated by TEC is removed from the heat sink by water circulating in the Water Cooling System.



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# NuMI (Neutrinos at the Main Injector) Beam



- Beam spectrum tunable by horn currents, relative placement of target and horns.
- Can select  $\nu$  or  $\bar{\nu}$  predominant beam depending on horn current polarity.
- $10\mu\text{s}$  beam spill (every 2.2 sec).
- Future: -700 kW power to NuMI using existing accelerator complex.
  - Reduce cycle time from 2.2 to 1.33 seconds.

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# Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Electroweak eigenstates                                  PMNS Mixing matrix                                      Vacuum eigenstates

$$P(\nu_a \rightarrow \nu_b) = \delta_{ab} - \sum_{j>i} \text{Re}(U_{ai}^* U_{bi} U_{aj} U_{bj}^*) \sin^2(1.27 \Delta m_{ij}^2 L/E) \pm \sum_{j>i} \text{Im}(U_{ai}^* U_{bi} U_{aj} U_{bj}^*) \sin^2(2.54 \Delta m_{ij}^2 L/E)$$

Now we are ready to build an experiment...

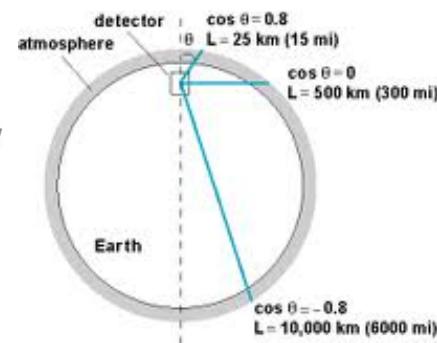
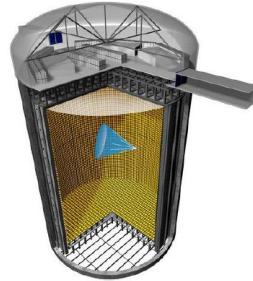
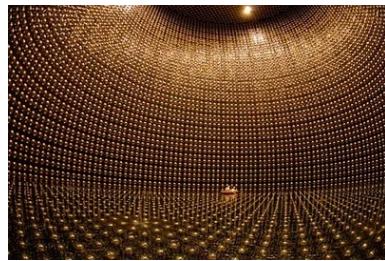


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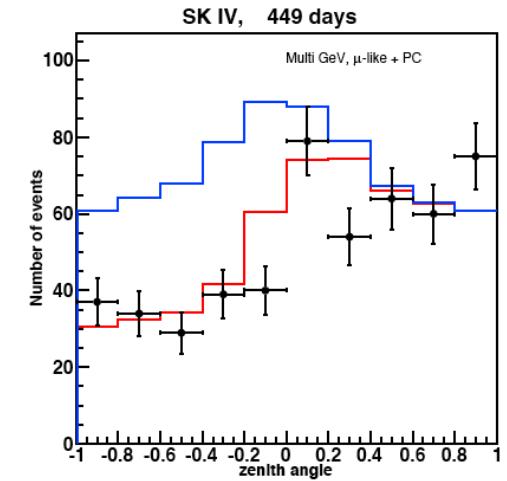
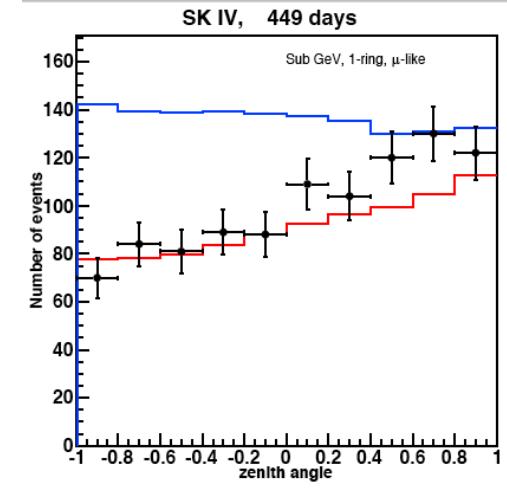
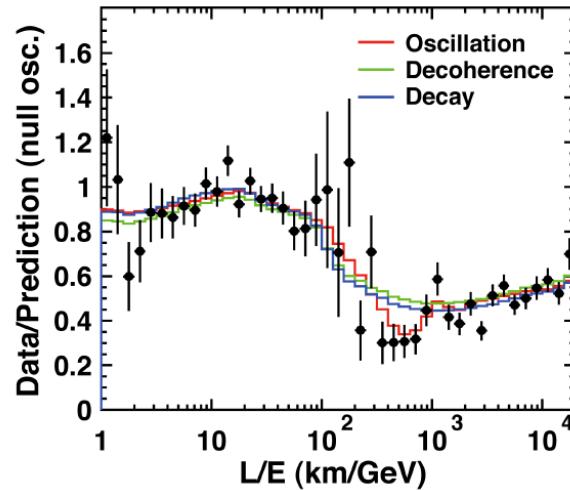


# Atmospheric $\nu$ oscillations

## Super-Kamiokande



By collecting  $\nu_\mu$  events as a function of the zenith angle the Super-Kamiokande experiment has discovered atmospheric neutrino oscillations

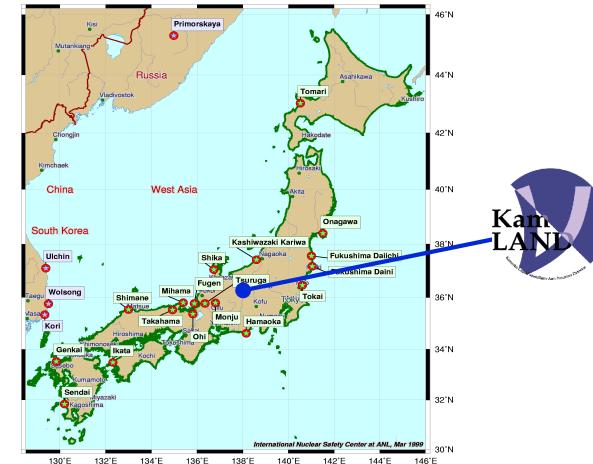
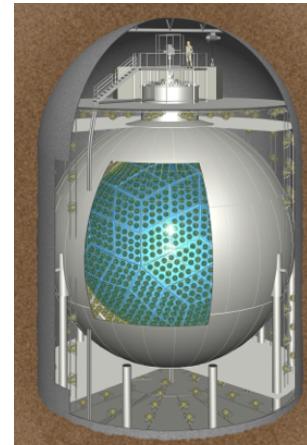


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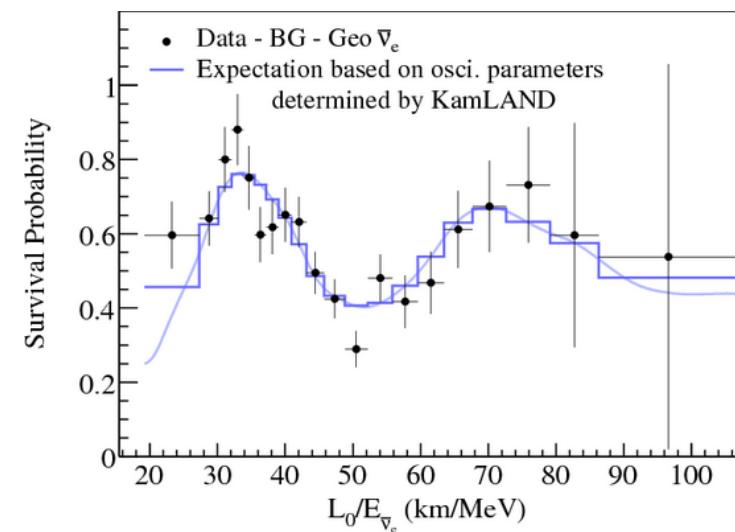


# Solar $\nu$ oscillations

## KamLAND



By collecting reactor  $\bar{\nu}_e$ , KamLAND experiment observed the solar neutrino oscillations.

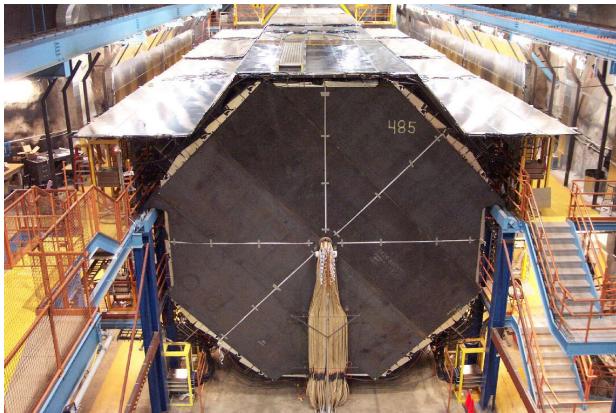


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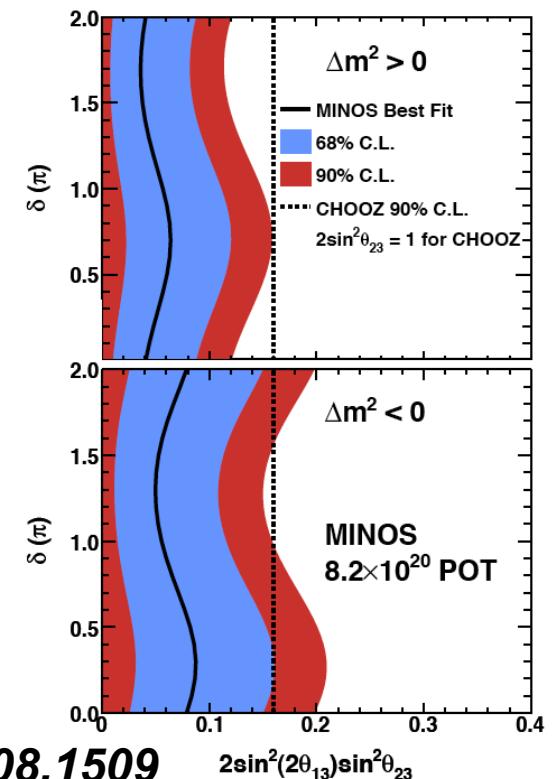


# Latest $\theta_{13}$ Results

## MINOS



By looking for  $\nu_\mu \rightarrow \nu_e$  oscillation MINOS finds new limits on  $\theta_{13}$



arXiv:1108.1509



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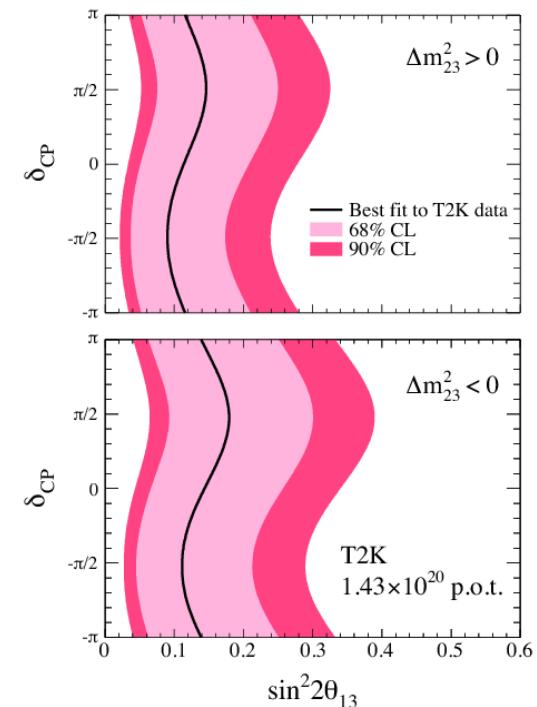


# Latest $\theta_{13}$ Results

## T2K



By looking for  $\nu_\mu \rightarrow \nu_e$  oscillation T2K found 6 candidate events with a predicted background of  $1.5 \pm 0.3$ . Thus, they report a measurement of a non-zero value of  $\theta_{13}$ .



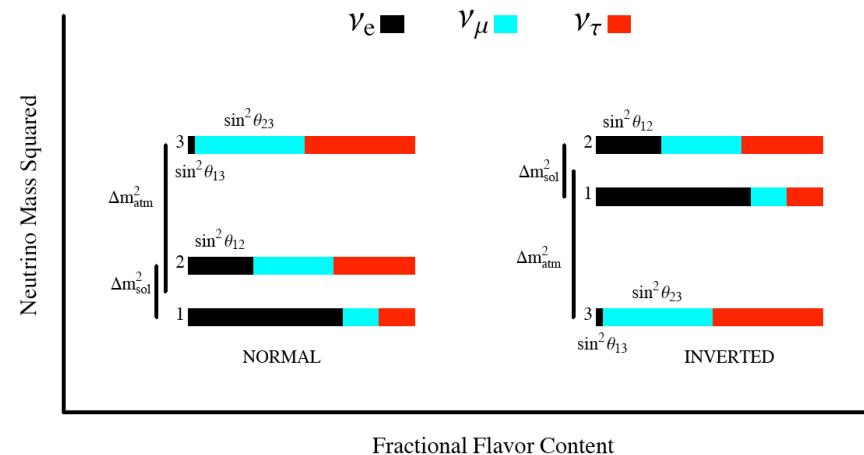
*Phys. Rev. Lett. 107, 041801*



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# Neutrino Oscillations



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

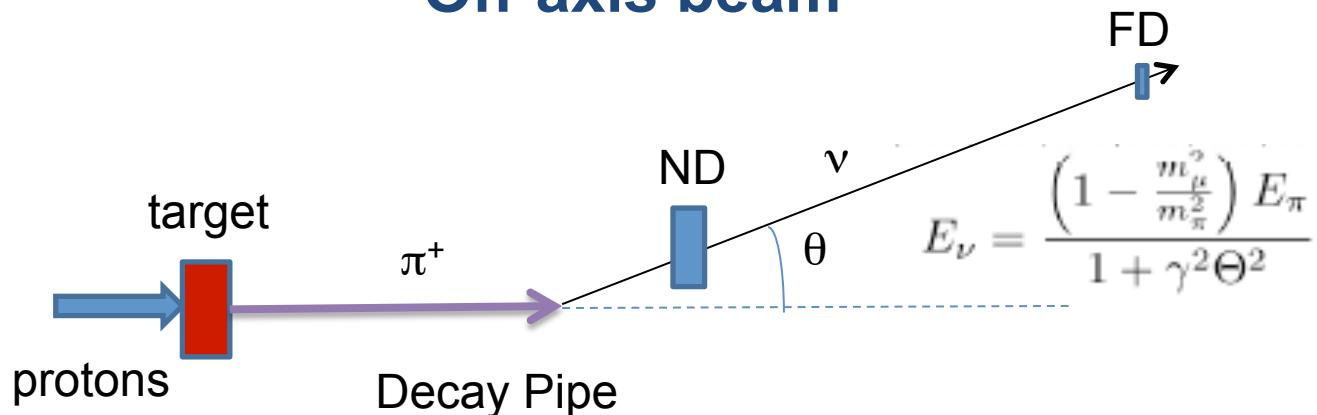
Determination of  $\delta$  depends on the value of  $\sin\theta_{13}$



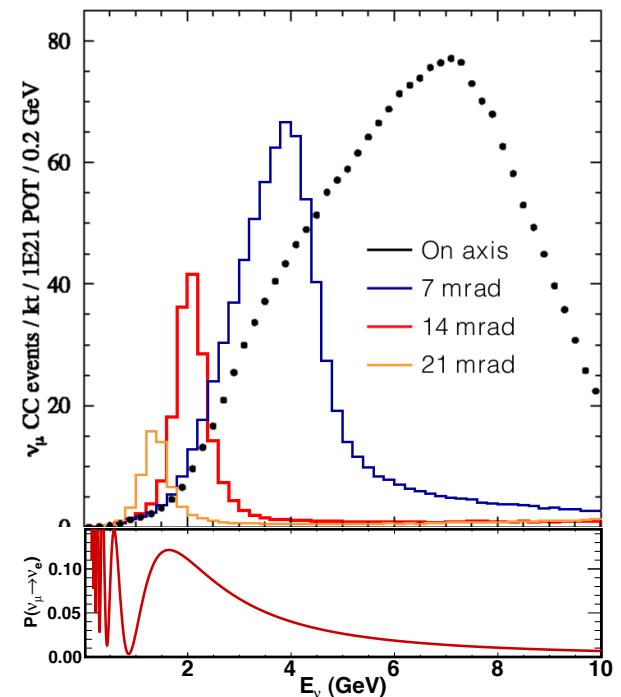
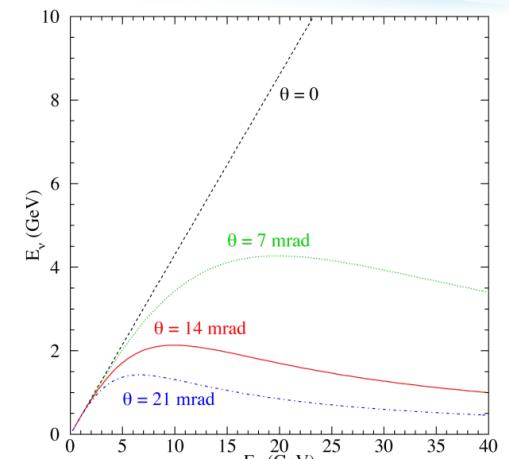
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## Off-axis beam



- Placing detectors 14 mrad off the beam axis results in 2GeV narrow band beam. Close to the oscillation maximum.
- Enhanced 700 kW NuMI beamline.
- Reduce cycle time from 2.2 to 1.3 seconds.
- Increased intensity/cycle with additional Booster batch.
- New horn and target.
- 10μs beam pulse every 1.3 seconds.
- 4.9e13 POT/pulse or 6e20 POT/year.

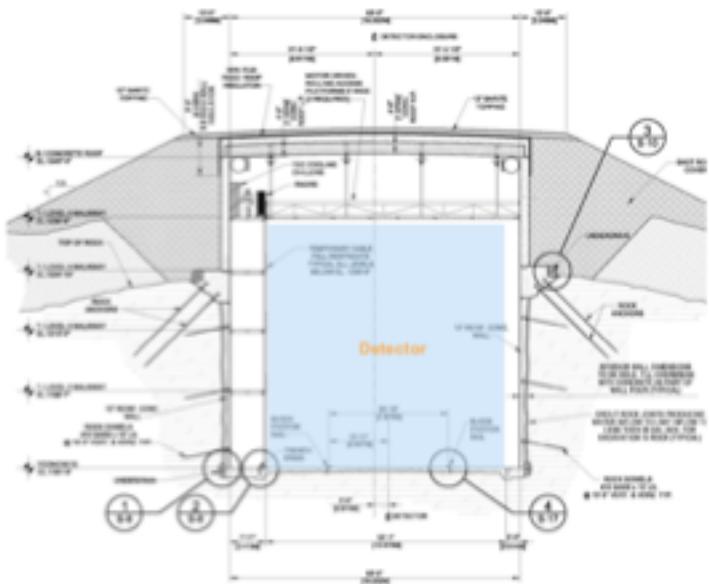


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# Far Detector

- Beneficial occupancy well under way
- Far Detector by the numbers:
  - 11.9 million liters of scintillator
  - 12,050 km of 0.7 mm optical fiber
  - 11,160 PVC modules and APDs
  - 357,120 channels



3m earth-equivalent  
overburden of Barite/  
Concrete  
to reduce cosmic  
backgrounds

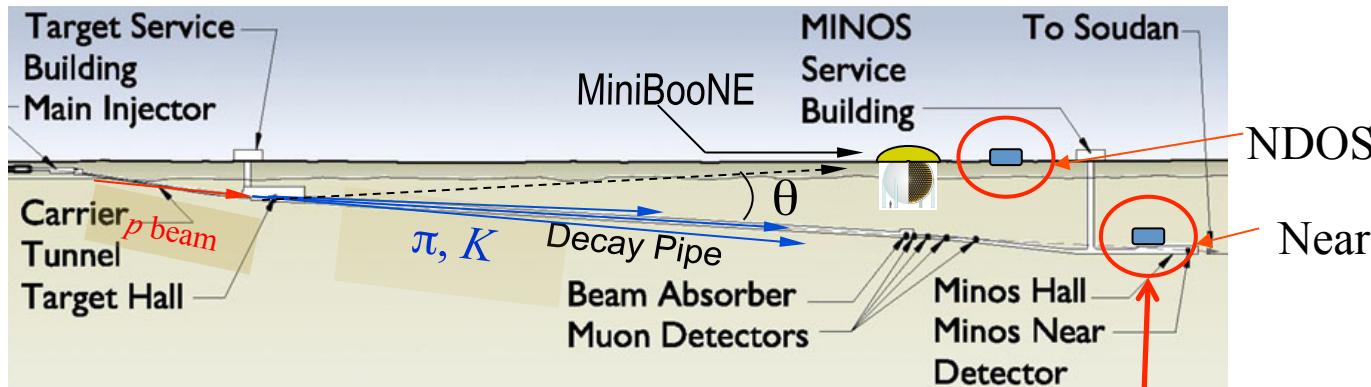
Soldier Field in Chicago IL, seats 61,500 fans



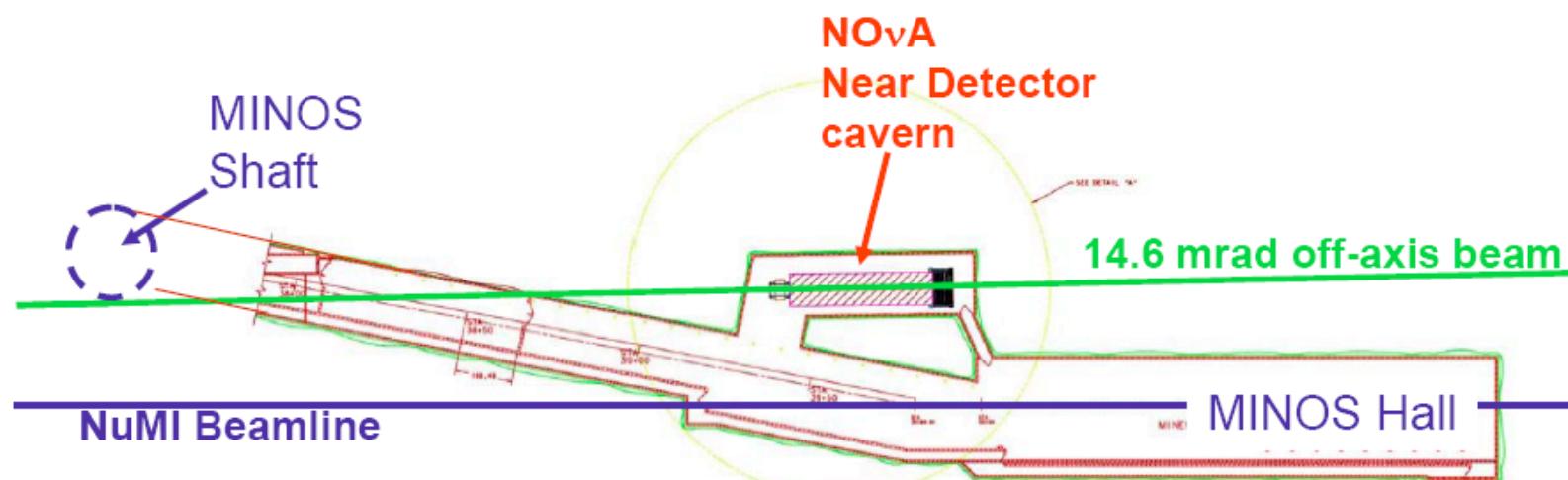
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# Near Detector



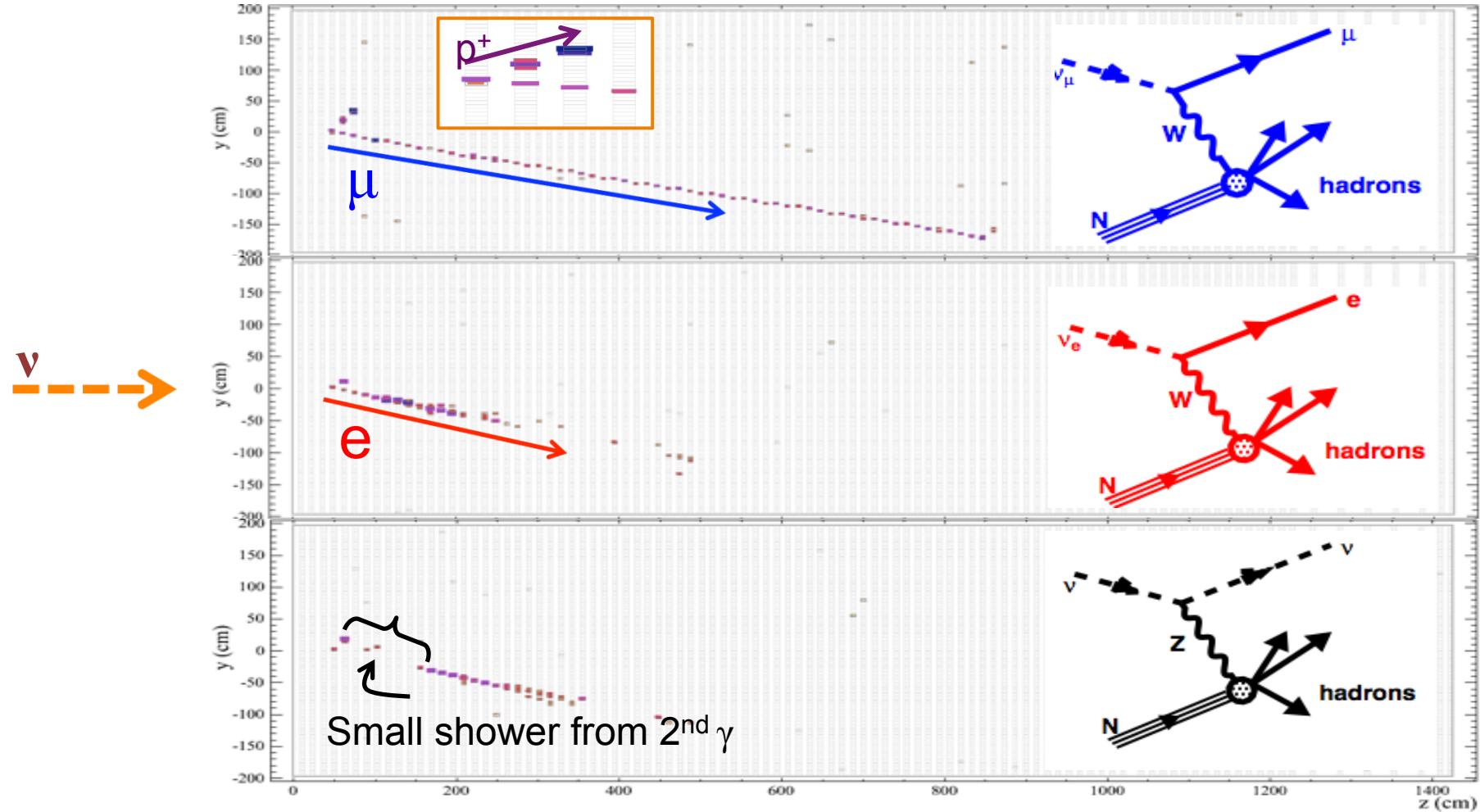
- Cavern for Near Detector to be excavated near MINOS Near Detector Hall.
- 1km from NuMI target.



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# Monte Carlo Simulations



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